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National Transonic Facility Wall Pressure Calibration Using Modern Design of Experiments (Invited)

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NATIONAL TRANSONIC FACILITY WALL PRESSURE CALIBRATION USING MODERN DESIGN OF EXPERIMENTS

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Abstract

The Modern Design of Experiments (MDOE) has been applied to wind tunnel testing at NASA Langley Research Center for several years. At Langley, MDOE has proven to be a useful and robust approach to aerodynamic testing that yields significant reductions in the cost and duration of experiments while still providing for the highest quality research results. This paper extends its application to include empty tunnel wall pressure calibrations. These calibrations are performed in support of wall interference corrections. This paper will present the experimental objectives, and the theoretical design process. To validate the tunnel-empty-calibration experiment design, preliminary response surface models calculated from previously acquired data are also presented. Finally, lessons learned and future wall interference applications of MDOE are discussed.

Nomenclature

Cp	Coefficient of Pressure
M	Mach number
P_T	Total Pressure
λ	Resolution of the response
σ	Standard Error in Response
ANOVA	Analysis of Variance
MDOE	Modern Design of Experiments
NTF	National Transonic Facility
OFAT	One Factor at a Time
WICS	Wall Interference Correction System

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Introduction

Tunnel empty wall pressure calibrations are required for use with most methods of wall interference corrections[1]. The calibration establishes the baseline pressure distributions on the walls during a tunnel empty environment. Without the presence of a model, the wall pressure distributions are a result of tunnel induced effects. These effects are generally referred to as orifice signatures and arise from several sources. Orifice signatures can stem from tunnel physical characteristics such as wall abnormalities and orifice imperfections. They can also stem from flow characteristics such as tunnel wall boundary layer effects. The tunnel empty calibration quantifies these effects as an orifice signature for each individual wall pressure orifice for a specific set of tunnel conditions. The magnitudes of these signatures are a function of tunnel conditions; therefore the range of the tunnel empty calibration defines the operational range in which wall corrections can be made. The National Transonic Facility (NTF) currently uses the wall interference code WICS to compute corrections for low-speed, subsonic solid-walled tests[2]. The wall corrections capability at the NTF is currently limited to only a portion of the air mode testing envelope of the facility by the tunnel empty calibration. Initially this was done to focus the implementation efforts. Now that this correction system is operational, a new calibration is required to expand the wall corrections ability to match the air mode solid wall testing capabilities of the NTF. A high quality definition of the orifice signatures is required from this calibration since tare corrections are made to aerodynamic test data by subtracting the tunnel empty signatures, thereby eliminating the baseline pressure variations. Obtaining this baseline signature over the proposed NTF test region can be cost prohibitive, since the flow conditions are widely varying functions of pressure, temperature, and Mach number. The development of MDOE methods for aerodynamic testing offers the potential of significantly lowering the cost and resource requirements of an experiment while still providing for the highest quality research result[3]. Rather than simply acquiring as much data as resources permit, the MDOE objective is to acquire enough data to meet the research requirements. The purpose of this paper is to apply the MDOE methods to tunnel empty wall pressure calibrations to capitalize on the benefits offered by this method of experimentation.

The Facility

The NTF is a unique transonic wind tunnel designed to conduct high Reynolds number testing through the use of high pressures and cryogenic temperatures[4]. The tunnel can be run using either air or nitrogen as the test medium. The range of test conditions for this facility is given in **Table 1**.

Table 1 – NTF Test Conditions

Pressure (psi)	$15 \le P_T \le 130$
Temperature (°F)	$-260 \le T \le 130$
Max Reynolds number	150 million/ft

There are approximately 470 static pressure orifices in the walls of the NTF. These pressure orifices are indexed by row numbers. The orientation of these rows with respect to the tunnel cross section is shown in **Figure 1**.

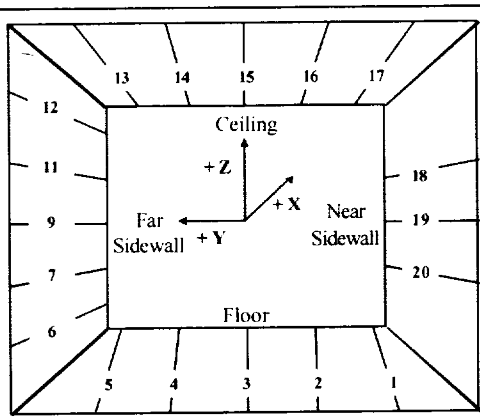

Figure 1: NTF Row Layout

Examples of the tunnel empty wall pressure distributions obtained from the current calibration are shown in **Figure 2**. For convenience, these data are plotted as the coefficient of pressure (Cp) versus axial tunnel location (X) for each row.

The Current Calibration

The current tunnel empty calibration used a conventional one factor at a time (OFAT) test technique. The calibration was structured to acquire three repeat data points per condition, and beginning and end-of-test replicates of each condition. The repeat data points were taken within the same run to observe the variation in the response. The beginning and end-of-test replicates were taken to estimate the overall process error. To allow for between condition interpolation, WICS required at least three different total pressure levels be taken at each test Mach number. Detailed analysis of the quality and consistency of this data set was performed to remove outliers and identify test anomalies. The range of this calibration is given in **Table 2**.

Table 2 – Range of Current Calibration

Mach number	$0.1 \le M \le 0.45$
Pressure (psi)	$15 \le P_T \le 90$
Temperature (°F)	95

This OFAT approach is not suitable for the next calibration due to the large amount of data, time, and resources that would be required to cover the entire air mode testing envelope of the NTF. **Figure 3** contrasts the range of the current and future calibrations in the NTF test envelope. It is important to note the difference in the lower limit on Mach number between these two calibrations. For the current calibration the lower limit was M=0.1, and for the future calibration this limit is M=0.2. A lesson learned from the current calibration is that wall pressures measured at M=0.1 are below the normal operational range of the wall instrumentation. The data taken at this condition contains too much instrument noise and was not acceptable for use in WICS.

The MDOE Calibration

Much of the improvements in testing through the MDOE approach are attributable to its relatively intense pre-test planning. This planning requires a thorough and quantitative statement of objectives, requirements, and data quality standards. It includes declaring the independent and dependant variables, their ranges, and measurement tolerances. A declaration for the type and quality of the expected result is also required. Following this initial planning, the testing sequence is optimized to account for both known and unknown sources of systematic error through sequence randomization and

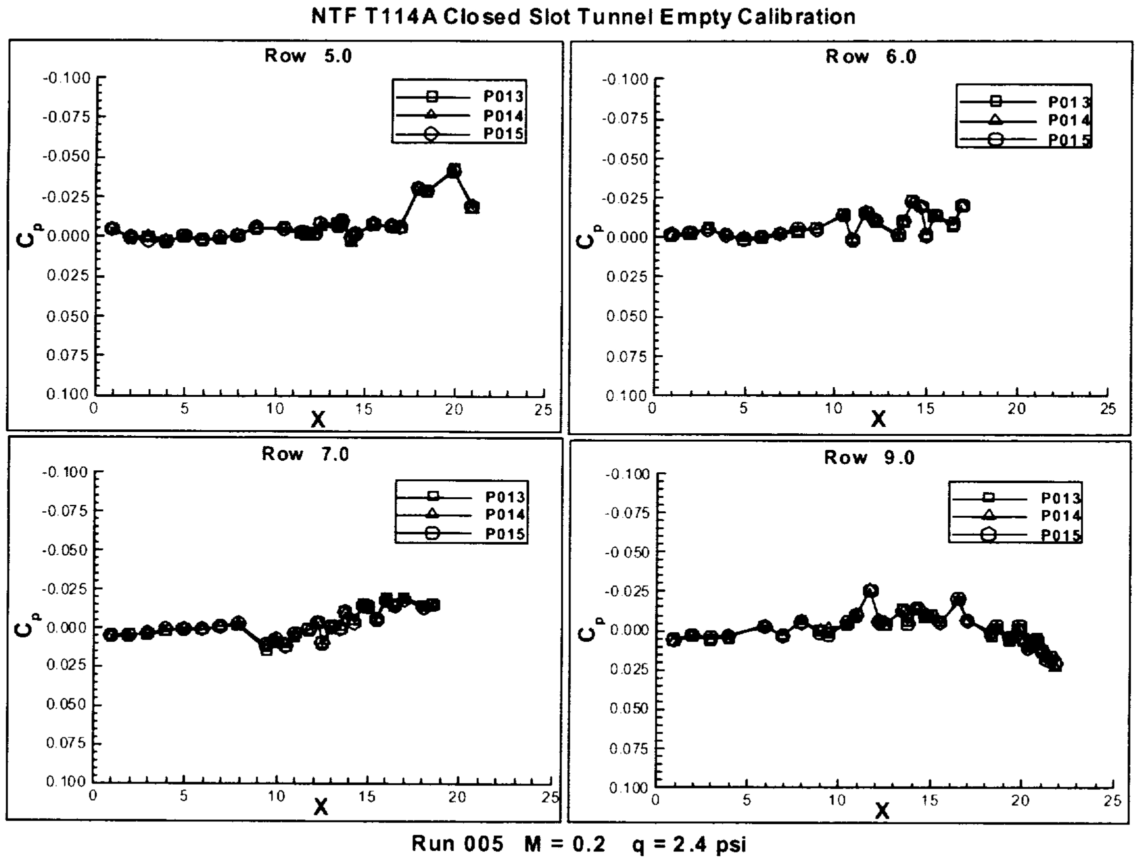

Figure 2: Tunnel Empty Wall Pressure Distributions

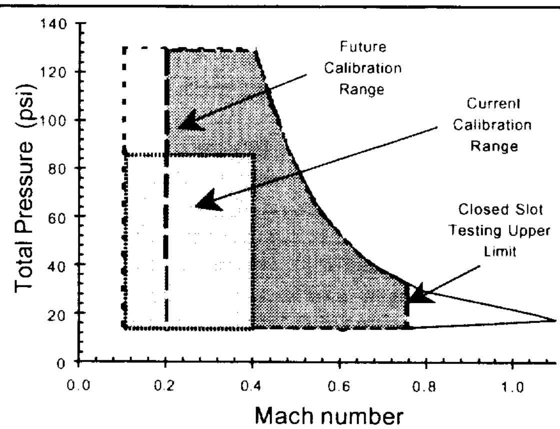

Figure 3: NTF Air Mode Test Envelope

orthogonal blocking[5]. The result generated from this experiment method is a response surface model for the dependant variable as a function of the independent variables. For this calibration, the response surface model will be for the wall pressure orifice as a function of tunnel Mach number and total pressure, or equivalently an equation that will predict the response in Cp due to changes in Mach number and total pressure. These response models establish a data quality standard on the tunnel empty calibration that will in turn improve the data quality of the wall interference corrections generated from WICS. They also provide an estimate of the interaction effects between the variables, which are not generally quantified in conventional OFAT testing. These response surface models will also simplify the application of the calibration data in the WICS code by using a functional representation rather than a data set to describe the orifice signatures. The tactics inherent in the MDOE approach provide for an overall improved wall interference calibration.

Wall Pressure Calibration Experiment Design

The objective of this experiment is to perform a tunnel empty wall pressure calibration to obtain response surface models that will describe the orifice signatures over the entire NTF air mode testing envelope (95°F) for a closed slot tunnel configuration. Since each orifice has a unique signature, a response surface model must be determined for every individual pressure orifice. This presents the potential for a significant amount of post-test analysis given that there are approximately 470 pressure orifices in the walls of the NTF. To keep this manageable, this calibration will serve as an exploratory experiment using a relatively simple design with the intent of defining more efficient modeling techniques.

Experiment Specifications

The predictor variables, or independent variables are defined as Mach number (M) and total pressure (P_T). The overall range of these variables is defined in **Table 3**. It is important to note that M=0.75 is the theoretical upper limit on Mach number for closed slot testing with nominally straight walls. The upper limit on Mach number will be verified prior to the start of the MDOE portion this experiment by setting the tunnel at the lowest total pressure condition and increasing the fan speed until there is no proportional change in Mach number, hence the tunnel choke point is determined.

Table 3 – Range of Independent Variables

Mach number	$0.2 \le M \le 0.75$
Total Pressure (psi)	$15 \le P_T \le 130$
Temperature (°F)	$95^o F$

The response variable of interest, or the dependant variable is defined as Cp. The data quality requirements are expressed in terms of the response variable. The acceptable standard error in Cp is defined as $\sigma = \pm 0.002$. This parameter was estimated from the known limitations of the instrumentation and the observable error found in historical wall calibration data. The required response resolution, or the smallest change in Cp that needs to be resolved, is defined as $\lambda = \pm 0.005$. This parameter was determined from historical wall calibration data and knowledge of the use of this data in WICS.

From the analysis of the current wall pressure calibration some consistencies in Cp were noticed. The magnitude of the individual orifice signatures changed with tunnel conditions, but the general trend of the wall pressure distributions remained the same. These magnitude changes in Cp plotted against the predictor variables (Mach number, and total pressure) produced a relationship that was approximately linear. For this reason it was assumed that the response model for Cp would not be greater than second order. These experiment specifications are summarized in **Table 4**.

Table 4 – Calibration Experiment Specifications

Independent Variables:	Mach number (M) Total Pressure (P_T) [psi]
Dependant Variable:	Wall Pressures (Cp)
Cp Data Quality Requirements:	σ=0.002 λ=0.005
Response Surface Model:	second order polynomial

The required data volume for this calibration is estimated to be 18 data points. This estimate was based on inference error risk tolerance specifications, data resolution requirements, and an estimate of the variance of the measurement environment using the methods discussed in reference 5.

The Central Composite Design

Using the experiment specifications and data volume requirement, the Central Composite Design[6] (CCD) was chosen for this experiment. The CCD can be considered a factorial experiment design augmented with additional points to facilitate quadratic model terms. The resulting design specifies each variable to occur at 5 levels. The CCD facilitates a model build-up process from an analysis of the data that makes comparisons, seeks similarities, differences, and trends[5]. These analysis characteristics work well with the exploratory intent of this calibration. Furthermore, such designs give rise to simple calculations that will help manage the volume of response surface models required to describe all the pressure orifices in the NTF. **Figure 4** gives a graphical depiction of this design. The 5 variable levels of the CCD can be categorized into three

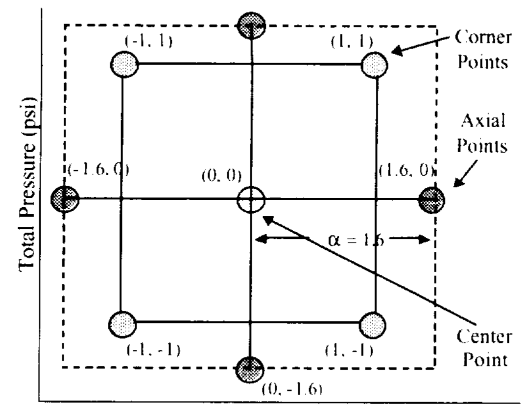

Figure 4: Central Composite Design

groups of design points. The first group is the factorial points or corner points. In coded (or scaled) variables these represent all the possible combinations of +/- 1, or the low and high variable levels[5]. The second group is the center points, and the third group is the axial points. The axial points are those in **Figure 4** which are located a distance α from the center. A typical second order CCD with 2 design variables consists of 12 data points. This includes the 4 corner points, the 4 axial points, and 4 replicate center points. To meet the calibration experiment data volume requirement, the corner and center points will be replicated. These replicates will also benefit the model build-up process by giving a better estimate of curvature and pure error in the system.

CCD experiments can be carried out in blocks. Blocking is a technique used to remove the expected variation caused by some change during the course of the experiment[7]. This will guard the calibration from expected variations that may occur due to shift changes or overnight testing breaks. The design points can be divided in such a way that these block effects are eliminated before the computation of the response model. This calibration will be carried out in two blocks. The first block consists of corner and center points, and the second block consists of axial and center points. The replicates of the corner points will be included in the first block, and the center point replicates will be divided between the two blocks. **Table 5** outlines the design points and their quantities for this experiment.

As mentioned earlier, the value of α determines the location of the axial points. In this calibration α is calculated to provide for block orthogonality. This

Table 5 – Wall Pressure Calibration Design Points

	Replicates	Number of Data Points
Block 1:		
Corner Points	2	8
Center Points	3	3
Block 2:		
Axial Points	1	4
Center Points	3	3
Total Number of Data Points:		**18**

means that the block effects are orthogonal to the regression coefficients in the second order response model so the blocks will not influence their determination[7]. For this calibration α=1.6.

Due to the large range of the independent variables, the test envelope was partitioned into 3 inference spaces. The first inference space represents a region that was mainly covered by the current OFAT calibration. This will provide for data comparisons between the two calibrations. The second inference space extends to the Mach number limit, and the third inference space extends the Reynolds number range and attempts to cover part of the curved region in the test envelope. Each of these inference spaces is required to meet the same experiment specifications listed above. A graphical depiction of these inference space designs containing actual test values is given in **Figure 5**. The rectangular nature of these inference spaces is a characteristic of the CCD. This characteristic shape makes fitting the curved region of the test envelope difficult. Variable transformations, or even a more complex experiment design may solve this curved region problem. These approaches are reserved for future iterations of this MDOE calibration, since this calibration is intended to be exploratory and provide for simple calculations.

All of the data points mentioned thus far are used in the calculation of the response model coefficients. Additional points are added to each inference space that will be used to determine how well the model predicts the orifice response. This experiment contains 6 confirmation points per inference space. This number should be sufficient based on the model inference error tolerances.

The final step in the design process is to randomize the order of the independent variables. Changing the variable levels sequentially yields responses confounded with systematic errors. Randomizing the

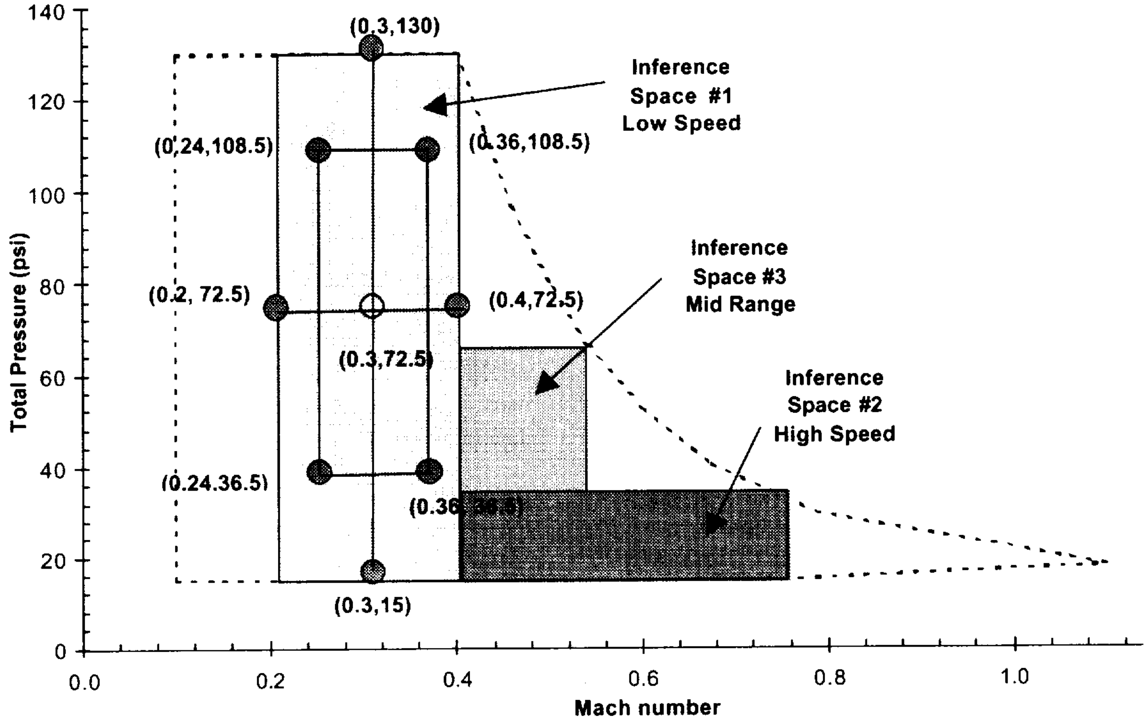

Figure 5: Three Inference Spaces in the NTF Test Envelope

order will ensure that the true effects are decoupled from systematic errors[5]. This experiment will contain within block and between block randomization, meaning that the data sequence within the blocks and the sequence of the blocks is randomized.

Response Surface Model Development

To validate the design, previously acquired data were used to calculate preliminary response surface models for a subset of the wall pressure orifices in the NTF. Using historical data in this design mandates cautious interpretation of the results since the data were not collected in the manner prescribed by the MDOE design and the factors are most likely not independent of each other. However, this exercise does allow for a preview of the response model terms and their interactions with other variables as well as provide for an opportunity to gain experience generating response surface models for the tunnel empty calibration. Based on the results from this analysis, changes or adaptations can be made to the experiment design that may better suit the tunnel empty calibration.

Response Surface Model Example

For this example, the response model for the ceiling pressure orifice located in row 15 (centerline) at tunnel station 13 is generated. For reference, tunnel station 13 (x = 13ft) at the NTF is nominally the model center of rotation for most aerodynamic test articles[4]. The model generated in this example will represent the response of this ceiling pressure orifice within the range of the first inference space. The test matrix for this inference space is given in **Table 6**. This test matrix will reflect the random order in which the data are acquired, and the orifice response at these conditions.

The results of performing an analysis of variance[8] (ANOVA) on these data are presented in **Table 7**. For convenience, Mach number and total pressure are represented by A and B respectively. This ANOVA indicates that the B^2 term is insignificant to the overall response of the pressure orifice, suggesting that model reduction may improve this model. On the other hand, the model as constituted features no significant lack of fit[6]. Even though the statistics in **Table 7** indicate this full second order model is adequate, the insignificant second order term is removed from the next ANOVA iteration. The results from performing an ANOVA on this reduced second order model are presented in **Table 8**.

Comparing the ANOVA from the full second order model with the reduced second order model indicates that little was lost by dropping the second order term.

Table 6 – Inference Space #1 Ceiling Orifice Row 15 x = 13.5 ft

Run	Block	M	Pt	Cp
1	1	0.300	72.50	-0.00534
2	1	0.250	110.00	-0.00621
3	1	0.363	108.54	-0.00675
4	1	0.237	36.46	-0.01362
5	1	0.300	72.50	-0.00424
6	1	0.363	36.46	-0.00355
7	1	0.363	36.46	-0.00335
8	1	0.237	108.54	-0.00548
9	1	0.320	123.00	-0.00410
10	1	0.237	108.54	-0.00658
11	1	0.237	36.46	-0.01362
12	1	0.200	22.00	-0.03001
13	1	0.300	72.50	-0.00524
14	1	0.363	108.54	-0.00225
15	2	0.300	130.00	-0.00153
16	2	0.400	72.50	-0.00540
17	2	0.300	72.50	-0.00364
18	2	0.300	35.00	-0.00610
19	2	0.300	72.50	-0.00294
20	2	0.230	79.00	-0.00864
21	2	0.230	115.00	-0.00728
22	2	0.300	72.50	-0.00564
23	2	0.300	15.00	-0.00815
24	2	0.200	72.50	-0.01402

Some general conclusions can be drawn based on the results of this example. The response surface for this wall pressure orifice within the range of the first inference space is a second order polynomial. While the exact composition of this second order response surface model is not yet known, it has been shown that this experiment design is capable of producing a model that is an adequate predictor of this design space.

Response Surface Model Comparisons

Preliminary response surface models were generated using historical data for a subset of the wall pressure orifices in the NTF using the same procedures outlined in the previous sections. Cautious interpretation of the results is required due to the use of historical data. Nonetheless, general conclusions and trends were noted based on this exercise. The previous example approximated the response surface model for the ceiling pressure orifice located in row 15 (centerline) at tunnel station 13 within the range of the first inference space. This model was a second order polynomial. The same wall pressure orifice evaluated within the range of the second inference space produced a response model that was less dependent on the second order terms. For this pressure orifice in the second inference space a model of the following form proved to be the best predictor.

$$Cp = \text{Intercept} + A + B + A^2$$

Again, Mach number and total pressure are represented by A and B respectively. In this model only the pure second order term A^2 representing Mach number is significant. This result seems logical given the limited range of the total pressure in this inference space. For this region, the Mach number and total pressure ranges are

$$0.4 \le M \le 0.75$$
$$15\,psi \le P_T \le 32\,psi$$

The relative change in M is larger than that of P_T. This may explain the larger dependence on M observed in this response model. The insignificant second order terms in this model may also be attributed to an improved instrumentation resolution at the higher test conditions. The data contains less instrument noise at these higher conditions where the instrumentation is within its normal operational range. The same wall pressure orifice evaluated within the range of the third inference space produced a linear response model. Again, indicating that the improved data resolution at these higher test conditions may produce a lower order response surface model

The preliminary response surface models for other wall pressure orifices in these three inference spaces produced very similar results. The order of the models is largely dependant on the inference space or the range of the independent variables. All the models for the first inference space were generally second order polynomials. The models for the second inference space were also second order, but gave implications they were only dependant on the second order Mach number term. However, the

Table 7 – ANOVA for Full Second Order Response Surface Model						
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob F**	
Block	9.138E-007	1	9.138E-007			
Model	2.349E-004	5	4.698E-005	31.22	0.0001	Significant
Terms						
A	1.054E-004	1	1.054E-004	70.05	0.0001	Significant
B	4.272E-005	1	4.272E-005	28.38	0.0002	Significant
AB	3.738E-005	1	3.738E-005	24.84	0.0004	Significant
A^2	4.927E-005	1	4.927E-005	32.74	0.0001	Significant
B^2	3.610E-007	1	3.610E-007	0.24	0.6339	Not Significant
Residual	1.656E-005	11	1.505E-006			
Pure Error	1.542E-005	8	1.927E-006			
Lack of Fit	1.140E-006	3	3.799E-007	0.20	0.8955	Not Significant

Standard Deviation	1.227E-003	R-Squared	0.9342
Mean	-6.185E-003	Adj R-Squared	0.9042
Adequate Precision	16.056	Pred R-Squared	0.8327

Table 8– ANOVA for the Reduced Second Order Response Surface Model						
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob F**	
Block	9.138E-007	1	9.138E-007			
Model	2.346E-004	4	5.864E-005	41.60	0.0001	Significant
Terms						
A	1.054E-004	1	1.054E-004	74.79	0.0001	Significant
B	4.272E-005	1	4.272E-005	30.30	0.0001	Significant
AB	3.738E-005	1	3.738E-005	26.52	0.0001	Significant
A^2	4.902E-005	1	4.902E-005	34.77	0.0001	Significant
Residual	1.692E-005	12	1.410E-006			
Pure Error	1.542E-005	8	1.927E-006			
Lack of Fit	1.501E-006	4	3.751E-007	0.19	0.9344	Not Significant

Standard Deviation	1.187E-003	R-Squared	0.9327
Mean	-6.185E-003	Adj R-Squared	0.9103
Adequate Precision	18.497	Pred R-Squared	0.8469

response models for the third inference space were generally linear. These trends show promising means in which the analysis process may be simplified, however they need to be verified through the actual calibration data prior to making any process or design changes.

Overall, the experiment specifications assumed in the design process proved to be valid and yield an experiment design capable of producing response surface models that adequately predict the orifice response within the three inference spaces of the NTF test envelope.

Future MDOE Wall Interference Applications

Based on the results from this wall pressure calibration, the next generation design will include provisions to cover the curved region of the NTF test envelope. This is the region that was difficult to fit using the simple CCD experiment. Coordinate transformations or a more complex design can be used to address this region. The response surface models generated from this calibration will give more information as to which of these two approaches would be more appropriate. Another future use of the MODE method extends this calibration to the NTF cryogenic test envelope. This mode uses nitrogen rather than air as the test medium. However, the use of nitrogen can substantially increase the cost of an experiment. MDOE can reduce the cost of this experiment while still providing for high quality calibration results. Another type of calibration performed for use with wall interference corrections includes the model support system. This tunnel empty calibration specifically supports the semi-span model application of wall interference corrections. The application of WICS to full-span models requires the model support system in the test section during the calibration. For full-span models, tare corrections are made to the aerodynamic test data by subtracting the empty tunnel/model support system calibration data. For these types of wall pressure calibrations the support system is cycled through the scheduled test pitch or sideslip angles to quantify the effect of the support system on the wall pressure orifices. For this calibration, the support system effect is factored into the overall orifice signatures. The number of independent variables would change for this calibration to include the support system pitch and or sideslip angles, but the basic approach outlined in this paper would still apply. The use of MDOE for wall interference development opens up testing opportunities like these that might otherwise have been impractical due to cost or time constraints.

Conclusions

The goal of this wall pressure calibration experiment is to generate a response surface model per wall pressure orifice that will predict the orifice signature for a given inference space within the NTF air mode test envelope. This paper has presented the experiment specifications and stepped through the design process necessary for creating this experiment. Through the preliminary response surface models general trends were noted. These trends primarily indicate the difference in the order of the response models between each of the three inference spaces. If these trends are again observed in the response model generation from the actual wall pressure calibration, they can present a means of reducing the amount of post-test analysis. Furthermore, comparisons of the magnitude of the response model coefficients within and between the inference spaces may also reveal more efficient modeling techniques. This kind of detailed analysis is reserved for the actual wall pressure calibration since the historical data may give rise to false results. Overall, the preliminary response surface model exercise verifies that this experiment design is capable of producing response models that adequately predict the orifice signatures within the three NTF inference spaces. The experience and results obtained from this wall pressure calibration will provide the baseline information needed to apply MDOE to future wall interference applications.

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